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Study on Wire Rope Brace Design Method of Prestressed Braced Steel Moment Frame

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Abstract: To study the design method of sectional area and initial tension of wire rope brace of the prestressed braced steel moment frame structure system, theoretical analysis of this structure system is conducted in this paper. The lateral stiffness formula is derived. It reveals the lateral stiffness is related to the lateral stiffness of bare steel moment frame, story height, the distance between column and lower end of brace, story drift, material properties and sectional properties of wire rope. The lateral stiffness increases with the growth of story drift and the relationship curve is a concave shape. It is presented the initial prestress degree design formula and method in light of the criterion for determining initial prestress degree. The story drift decreases with the growth of wire rope sectional area and the relationship curve is a concave shape, in terms of this, a wire rope sectional area design formula and method are proposed. The validation of the proposed design formula and method of wipe rope brace is proved by an example analyzed using finite element software package ABAQUS.

Keywords: Design method, initial tension, sectional area, prestressed braced steel moment frame, wire rope brace.

1. INTRODUCTION

Moment-resisting steel frames in regions of high seismicity are commonly designed to have high lateral stiffness to restraint the lateral story displacement within a specified range [1]. However, unexpected events, such as extremely severe earthquakes, might cause unacceptably large story drift. Important tasks in structure design are the characterization of maximum story drift and damage distribution induced into building frames under a given external load. The maximum story drift has been regarded as the primary index for assessing the overall damage to a building.

Previous researches have underscored the necessity of lateral stiffness retrofitting of existing steel moment frames. There are several types of retrofitting methods have been investigated, such as thin infill panels [2] and bracing system. The bracing system can increase the story lateral stiffness and strength effectively. For improving the seismic resistance in the bracing members, an eccentrically braced frame [3, 4], a dissipative bracing system [5], a displacement-restraint bracing [6] and a non-compression brace [7] have been improved. An ordinary braced frame has complicated restoring force characteristics under seismic loading due to compressive brace buckling [8]. Buckling-restrained brace [9] has been investigated to prevent buckling occurrence in the bracing members, but it has complex details and heavy-weight. The brace system with semi-active and active control has been proposed and investigated to maintain the structure system in a non-resonant state [10, 11]. Some researchers have examined the application of these braces [12, 13].

The prestressed braced steel moment frame (PBSMF) presents a retrofit method using wire rope (cable) bracing for steel moment frame. It is an innovation using flexible wire rope (cable) instead of rigid brace. All the wire ropes in PBSMF have initial tensile force. Previous study on PBSMF demonstrates that it can increase the lateral stiffness and guarantee story drift in a specified range, as well as reduce the residual deformation [6]. By optimizing the initial tensile force of wire ropes, PBSMF can prevent buckling from occurring in the bracing members. Compared with other bracing systems, it is characterized by smaller weight and sectional area, which makes it easier to move and install. It is an essential problem how to determine the sectional area and initial tensile force of the wire ropes in PBSMF.

Theoretical analysis is conducted to investigate the performance of PBSMF in this paper. It is derived that the design formulas of sectional area and initial tensile force of wire rope brace in light of theoretical analysis results. Based on the specified story drift, a design method of sectional area and initial tensile force is proposed. The design method can optimize wire ropes with a smaller sectional area and more reasonable initial tension. An example of four-story three-

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1874-1495/15

$$\Delta L_2^x = L_2^x - L_2^0 \tag{9}$$

The deformation of wire rope under axial external loads is portrayed in Fig. (**4**), where T is initial tensile force of wire rope, L respects the initial length of wire rope without any tension, L^0 respects the length of wire rope under T, l_c respects the tensile length of wire rope under T. In terms of Hooke law and geometrical relationship shown in Fig. (**4**), the relationship between tensile length and initial prestress degree can be expressed as the following equation:

$$l_c = \gamma f_u L^0 / (\gamma f_u + E_C) \tag{10}$$

3.3. Initial Prestress Degree Formula of SDWRB

As described in Section 3.1, the initial prestress degree criterion of SDWRB is that the tensile stress of SDWRB is more than zero under designed external loads. It also can be written as the following geometrical form:

$$\Delta L_1^x < l_c \tag{11}$$

By substituting Eq. (8) and Eq. (10) into Eq. (11), we obtain

$$\gamma > \frac{E_C}{f_u}\left(\frac{\sqrt{H^2+B^2}}{\sqrt{H^2+(B-x)^2}} - 1\right) \tag{12}$$

Eq. (12) is the initial prestress degree formula of SDWRB, it gives the lower limit value of initial prestress degree of wire rope.

3.4. Initial Prestress Degree Formula of SIWRB

As described in Section 3.1, the initial prestress degree criterion of SIWRB is that the tensile stress of SIWRB is less than the designed acceptable stress under designed external loads. It also can be written as the following geometrical form:

$$l_c + \Delta L_2^x < l_{de} \tag{13}$$

where, l_{de} denotes the designed acceptable tensile length of wire rope, it can be calculated by Eq. (10).

By substituting Eq. (9) and Eq. (10) into Eq. (13), we obtain

$$\gamma < \frac{\sqrt{H^2+B^2}(E_C + f_{de})}{\sqrt{H^2+(B+x)^2}\, f_u} - \frac{E_C}{f_u} \tag{14}$$

where, f_{de} is the designed acceptable stress of wire rope.

Eq. (14) is the initial prestress degree formula of SIWRB, it gives the upper limit value of initial prestress degree of wire rope.

3.5. Initial Prestress Degree Formula of Wire Rope Brace

The wire rope brace of PBSMF consists of SDWRB and SIWRB. It is indeterminate that the wire rope brace is SDWRB or SIWRB, due to the uncertainty of the direction of external loads. Thereby, it is necessary to consider both the initial prestress degree of SDWRB and SIWRB in determining the initial prestress degree of wire ropes of PBSMF. In light of the results of Section 3.3 and 3.4, the initial prestress degree formula of wire rope brace, which must satisfy the Eq. (12) and Eq. (14) simultaneously, can be obtained in the following form:

Eq. (15) provides the range of initial prestress degree of wire ropes, which can be used to guide the design working of the PBSMF. Eq. (15) demonstrates that the initial prestress degree is only related to story drift while the members of PBSMF are determined, and there is no correlation between initial prestress degree and sectional area of wire ropes.

$$\begin{cases} \gamma > \dfrac{E_C}{f_u}\left(\dfrac{\sqrt{H^2+B^2}}{\sqrt{H^2+(B-x)^2}} - 1\right) \\ \gamma < \dfrac{\sqrt{H^2+B^2}(E_C + f_{de})}{\sqrt{H^2+(B+x)^2}\, f_u} - \dfrac{E_C}{f_u} \end{cases} \tag{15}$$

4. DESIGN METHOD OF WIRE ROPE BRACE

The determination of sectional area and initial prestress degree of wire rope brace is a pivotal problem in the design of PBSMF. Eq. (6) in Section 2 demonstrates that the lateral stiffness of PBSMF is related to sectional area of wire rope brace, thus, the story drift of PBSMF under external loads has relation with sectional area of wire rope brace. Thereby, we can design the sectional area of wire rope with respect to the relationship between the sectional area of wire rope and the story drift of PBSMF.

According to Eq. (2) and Eq. (6), we can obtain

$$\begin{aligned} dP &= D_f dx + D_C dx \\ D_C &= \left(1 - \frac{\sqrt{H^2+(B-x-1)^2}}{\sqrt{H^2+(B-x)^2}}\right) E_C A_C \cos\left(\arctan\frac{H}{B-x-1}\right) \\ &\quad + \left(\frac{\sqrt{H^2+(B+x+1)^2}}{\sqrt{H^2+(B+x)^2}} - 1\right) E_C A_C \cos\left(\arctan\frac{H}{B+x+1}\right) \end{aligned} \tag{16}$$

where, dx denotes the tiny story drift.

Integrating Eq. (16) gives the function of the horizontal external load with respect to story drift as follows:

where, p is the total number of SDWRB, k is the number of SDWRB, A_{kC} is the sectional area of SDWRB k, m is the total number of SIWRB, j is the number of SIWRB, A_{jC} is the sectional area of SIWRB j.

In terms of Eq. (17), it is portrayed the relations of wire rope sectional area and story drift of PBSMF in Fig. (**5**), while other parameters are determined. Fig. (**5**) indicates that story drift decreases with the growth of wire rope sectional area, and the curve is a concave shape.

Eq. (15) demonstrates that the lateral stiffness of PBSMF has no correlation with initial prestress degree of wire rope brace. It is proposed a design method of the sectional area and initial prestress degree of wire rope brace in PBSMF in light of Eq. (15) and Eq. (17).

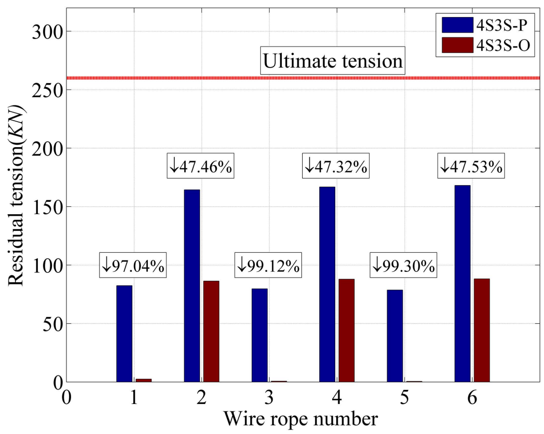

Fig. (11). Residual tension comparison of wire ropes in second floor.

Fig. (12). Residual tension comparison of wire ropes in third floor.

Fig. (13). Safe capacity comparison of wire ropes in first floor.

method in this paper. The residual tension of SIWRB and SDWRB reduces to 45.86% and 96.33% at most in the first story respectively, it reduces to 47.53% and 99.30% at most in second story respectively, and it reduces to 48.58% and 98.00% in third story respectively. The residual tension of SDWRB is almost to zero, which reveals the optimized initial tension is close to the minimum initial tension which can make sure the SDWRB doesn't quit working under the designed external loads.

5.5. Safe Capacity Comparison

The safe capacity of wire rope brace in each story is listed in Table **7**, Table **8** and Table **9** and portrayed in Fig. (**13**), Fig. (**14**) and Fig. (**15**). The safe capacity is increased effectively by using the design method proposed in this paper. The safe capacity of SIWRB and SDWRB increases to 45.86% and 96.33% at most in the first story respectively, it increases to 47.53% and 99.30% at most in second story respectively, and it increases to 48.58% and 98.00% in third story respectively. The safe capacity value of SDWRB is almost one, it indicates the SDWRB is almost in the safest state.

6. CONCLUSIONS

This study proposes a prestressed braced steel moment frame structure system (PBSMF). It is an innovation using flexible wire rope (cable) instead of rigid brace in traditional

Fig. (14). Safe capacity comparison of wire ropes in second floor.

Fig. (15). Safe capacity comparison of wire ropes in third floor.

Table 3. Analysis results of lateral stiffness (MPa).

Story number	1	2	3	4
4S3S-N	15816.89	15301.47	15133.11	14744.64
4S3S-P	42374.00	34249.82	22994.34	14593.06
4S3S-O	44743.13	34999.53	23496.55	14804.27
4S3S-P /4S3S-N	267.90%	223.83%	151.95%	98.97%
4S3S-O /4S3S-P	105.59%	102.19%	102.18%	101.45%

Table 4. Analysis results of cable residual tension in first floor (KN).

Model	Cable 1	Cable 2	Cable 3	Cable 4	Cable 5	Cable 6
4S3S-P	119.77	262.86	123.23	256.76	127.75	251.27
4S3S-O	4.40	142.53	5.45	139.12	7.28	136.05
Rate of decrease	96.33%	45.78%	95.58%	45.82%	94.30%	45.86%

Table 5. Analysis results of cable residual tension in second floor (KN).

Model	Cable 1	Cable 2	Cable 3	Cable 4	Cable 5	Cable 6
4S3S-P	82.44	164.37	79.73	166.82	78.65	168.12
4S3S-O	2.44	86.35	0.70	87.89	0.55	88.21
Rate of decrease	97.04%	47.46%	99.12%	47.32%	99.30%	47.53%

Table 6. Analysis results of cable residual tension in third floor (KN).

Model	Cable 1	Cable 2	Cable 3	Cable 4	Cable 5	Cable 6
4S3S-P	37.39	72.45	36.16	73.81	35.67	74.57
4S3S-O	1.25	37.25	0.73	38.15	0.71	38.43
Rate of decrease	96.66%	48.58%	97.99%	48.31%	98.00%	48.46%

Table 7. Analysis results of cable safe capacity in first floor.

Model	Cable 1	Cable 2	Cable 3	Cable 4	Cable 5	Cable 6
4S3S-P	0.70	0.34	0.69	0.36	0.68	0.37
4S3S-O	0.99	0.64	0.99	0.65	0.98	0.66
Rate of increase	41.18%	87.80%	42.57%	82.18%	44.27%	77.52%

Table 8. Analysis results of cable safe capacity in second floor.

Model	Cable 1	Cable 2	Cable 3	Cable 4	Cable 5	Cable 6
4S3S-P	0.68	0.37	0.69	0.36	0.70	0.35
4S3S-O	0.99	0.67	1.00	0.66	1.00	0.66
Rate of increase	44.95%	81.24%	43.74%	84.35%	42.97%	86.61%

braced moment frame. Theoretical analysis is conducted to investigate the performance of PBSMF in this paper. The main conclusions are as follows:

1. The lateral stiffness formula of PBSMF is derived theoretically, and it indicates that the lateral stiffness of the PBSMF is related to the lateral stiffness of bare steel moment frame, story height, the distance between

Table 9. Analysis results of cable safe capacity in third floor.

Model	Cable 1	Cable 2	Cable 3	Cable 4	Cable 5	Cable 6
4S3S-P	0.66	0.35	0.68	0.34	0.68	0.33
4S3S-O	0.99	0.67	0.99	0.66	0.99	0.66
Rate of increase	48.70%	89.89%	46.98%	94.37%	46.04%	97.58%

column and lower end of brace, story drift, material properties and sectional properties of wire rope.

2. The lateral stiffness of PBSMF increases with the growth of story drift and the relationship curve is a concave shape.
3. The story drift of PBSMF decreases with the growth of wire rope sectional area and the relationship curve is a concave shape. In term of this, a wire rope sectional area design formula and method are proposed.
4. In light of the criterion for determining initial prestress degree, the initial prestress degree design formula and method are presented.
5. The validation of the proposed design formula and method of wipe rope brace is proved by an example analyzed by using finite element software package ABAQUS.

NOTATIONS

D = is the lateral stiffness of PBSMF

D_f = is the lateral stiffness of bare steel moment frame

D_c = is the lateral stiffness of wire rope brace

δ = is the unit story drift

δP = is the external load with respect to unit story drift

H = is the story height

B = is the distance between column and lower end of brace

x = is the story drift

P = is the horizontal external load with respect to story drift

L_1^x = is the length of SDWRB under P

L_2^x = is the length of SIWRB under P

α_1^x = is the angle between SDWRB and the horizontal plane under P

α_2^x = is the angle between SIWRB and the horizontal plane under P

$L_1^{x+\delta}$ = is the length of SDWRB under $P+\delta P$

$L_2^{x+\delta}$ = is the length of SIWRB under $P+\delta P$

$\alpha_1^{x+\delta}$ = is the angle between SDWRB and the horizontal plane under $P+\delta P$

$\alpha_2^{x+\delta}$ = is the angle between SIWRB and the horizontal plane under $P+\delta P$

ΔL_1^{δ} = is the compressed length of SDWRB under δP

ΔL_2^{δ} = is the tensile length of SIWRB under δP

ΔT_1 = is the decreased tension of SDWRB

ΔT_2 = is the increased tension of SIWRB

E_C = is the elastic modulus of wire rope

A_C = is the sectional area of wire rope

T_d = is the designed ultimate tension

F_d = is the designed external force

γ = is the initial pretress degree of wire rope

i = is the number of wire rope

n = is the total number of wire ropes

T_i = is the tensile force of wire rope i

L_1^0 = is the length of SDWRB in the initial prestress state

L_2^0 = is the length of SIWRB in the initial prestress state

α_1^0 = is the angle between SDWRB and the horizontal plane in the original model

α_2^0 = is the angle between SIWRB and the horizontal plane in the original model

ΔL_1^x = is the compressed length of SDWRB under P

ΔL_2^x = is the tensile length of SIWRB under P

T = is the initial tensile force of wire rope

L = is the initial length of wire rope without any tension

L^0 = is the length of wire rope under T

l_c = is the tensile length of wire rope under T

l_{de} = is the designed acceptable tensile length of wire rope

f_{de} = is the designed acceptable stress of wire rope

dx = is the tiny story drift

k = is the number of SDWRB

p = is the total number of SDWRB

j = is the number of SIWRB

m	=	is the total number of SIWRB
A_{kC}	=	is the sectional area of SDWRB k
A_{jC}	=	is the sectional area of SIWRB j.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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REFERENCES

[1] M. Bruneau, C. M. Uang, and A. Whittaker, *Ductile Design of Steel Structures*. NewYork: McGraw-Hill, 1998.

[2] M. Bruneau and T. Bhagwagar, "Seismic retrofit of flexible steel frames using infill panels", *Eng. Struct.*, vol. 24, pp. 443-453, 2002.

[3] M. Bosco, and P.P. Rossi, "Seismic behaviour of eccentrically braced frames", *Eng. Struct.*, vol. 31, pp. 664-674, 2009.

[4] G. Yiğitsoy, C. Topkaya, and T. Okazaki, "Stability of beams in steel eccentrically braced frames", *J. Construct. Steel Res.*, vol. 96, pp. 14-25, 2014.

[5] E. Renzi, S. Perno, and S. Pantanella, "Design, test and analysis of a light-weight dissipative bracing system for seismic protection of structures", *Earthq Eng. Struct. Dyn.*, vol. 36, pp. 519-539, 2007.

[6] X. Hou, and H. Tagawa, "Displacement-restraint bracing for seismic retrofit of steel moment frames", *J. Construct. Steel Res.*, vol. 65, pp. 1096-1104, 2009.

[7] H. Tamai, and T. Takamatsu, "Cyclic loading tests on a non-compression brace considering performance-based seismic design", *J. Construct. Steel Res.*, vol. 61, pp. 1301-1317, 2005.

[8] R. Tremblay, "Inelastic seismic response of steel bracing members", *J. Construct. Steel Res.*, vol. 58, pp. 665–701, 2002.

[9] Q. Xie, "State of the art of buckling-restrained braces in Asia", *J. Construct. Steel Res.*, vol. 61, pp. 727-748, 2005.

[10] P. Nikos, and G. Charis, "Design and control algorithm for structures equipped with active variable stiffness devices", *Struct. Control. Health Monit.*, vol. 17, pp. 591-613, 2010.

[11] T. Kobori, M. Takahashi, and T. Nasu, "Seismic response controlled structure with active variable stiffness system", *Earthquake. Eng. Struct. Dyn.*, vol. 22, pp. 925-941, 1993.

[12] F. Bartera, and R. Giacchetti, "Steel dissipating braces for upgrading existing building frames", *J. Construct. Steel Res.*, vol. 60, pp. 751-769, 2004.

[13] L. D. Sarno, and A. S. Elnashai, "Bracing systems for seismic retrofitting of steel frames", *J. Construct. Steel Res.*, vol. 65, pp.452-465, 2009.

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